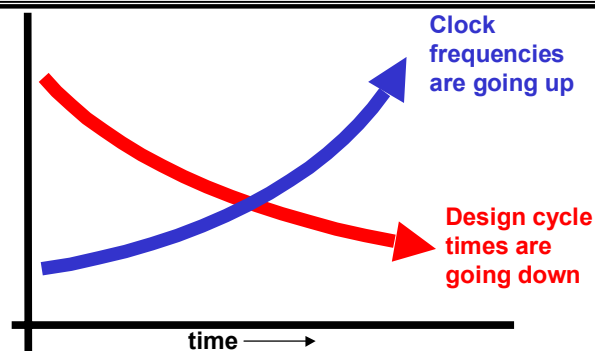

Frequency Domain Characterization for Digital Applications

Dr. Eric Bogatin
CTO, GigaTest Labs
eric@GigaTest.com
www.GigaTest.com

High Speed Product Design will only get **Harder**



- Key ingredient to the new high speed design methodology: **predictability**
- Measurements are essential to reduce **risk**

Risk Reduction Through Measurements

- Create a model from a real structure (library creation, spec validation)
- Validate a model and simulation from a calculation (anchor to reality)
- Emulate the system level performance (Physical Layer Characterization)

VNA and TDR Based Measurements

- **When an external precision signal is required**
- **Applies to any passive interconnect or component**
 - Discretes
 - Packages
 - Connectors
 - PCB structures
 - Material properties



A Precision Instrument is Not Enough!

Component to characterize \rightarrow ? \rightarrow Instrument \rightarrow ? \rightarrow Valuable information



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Complete Characterization System Solutions

TDA Systems IConnect

TDR

DUT + microprobes

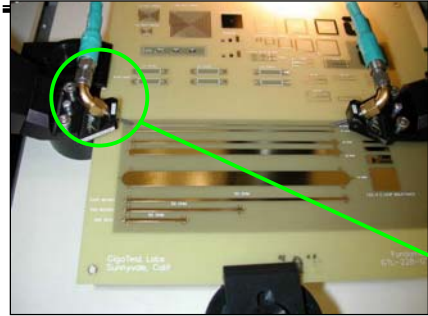
GigaTest Probe Station

Physical Layer Test System (PLTS): VNA + software

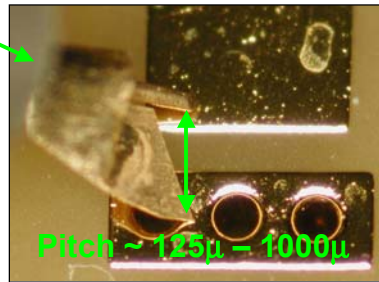
www.GigaTest.com

Slide - 7

Microprobes Allow Precision Probing of *GigaTest Labs* Structures with Minimal Artifacts



Close up

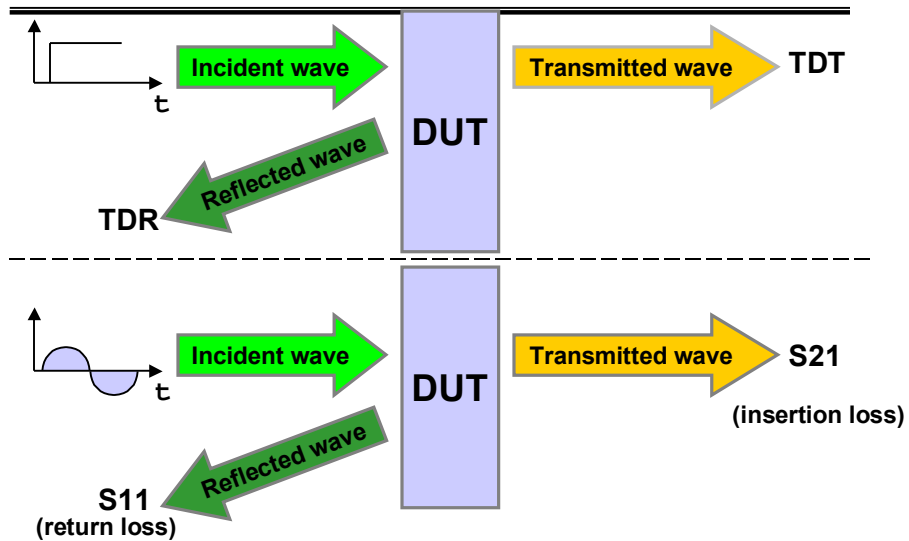


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Slide - 8

GigaTest Labs

TDR and VNA Techniques



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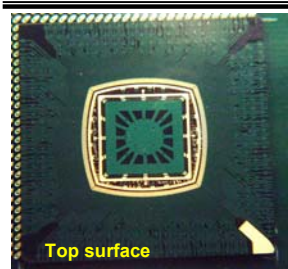
TDR and VNA Systems: What's the Difference?

- Fundamentally no new information in the frequency domain compared with the time domain
- Great deal of overlap in features, capabilities:
T lines, discontinuities, cross talk, differential impedance, ...
- A TDR is simple to use and can be quickly set up for general applications: transmission lines and discontinuities
- SNR is better for VNA than TDR
 - ✓ important for low insertion loss components
 - ✓ Important for low levels of mode conversion
- The PLTS simplifies the analysis of 4 port differential interconnects

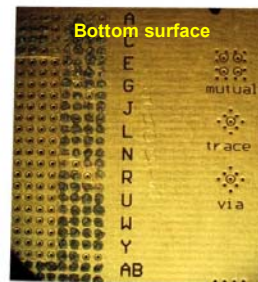
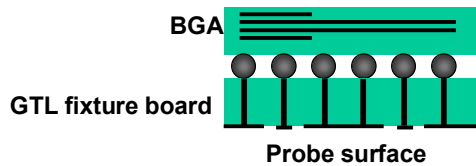
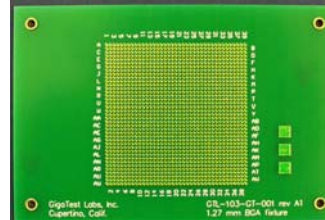
Case Study Examples

- Search for resonances
- Building high bandwidth interconnect models
- 2 port measurements:
 - ✓ Return loss and impedance matching
 - ✓ Insertion loss, attenuation and bandwidth of the interconnect
- 4 Port complete differential pair characterization

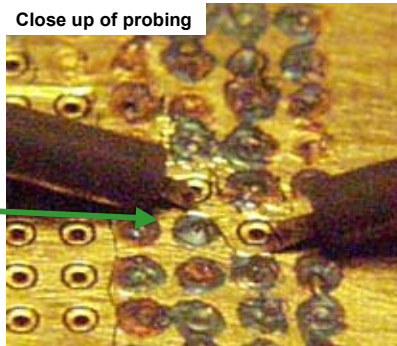
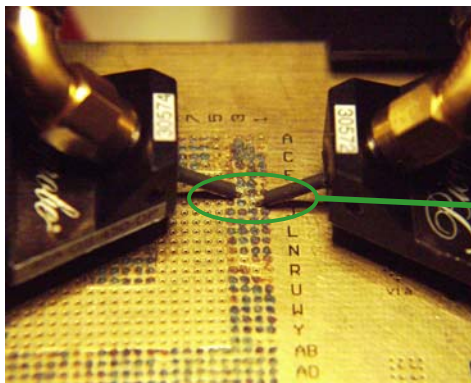
GigaTest Fixturing for Packages



Top pad surface of GTL Fixture board



Probing of Bottom Fixture Board



Shorted to bottom ref plane

Return path is all the pwr, gnd balls

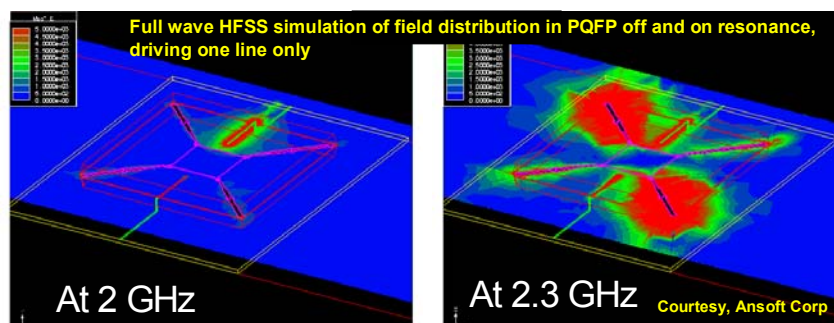
Return Loss from One BGA Lead

Open at far end



What are the curly-queues?

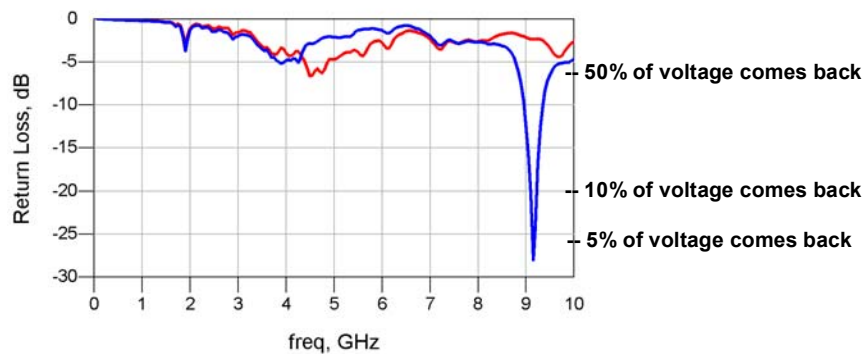
Package Resonances



- Package resonance effects can be modeled with full wave solvers
- They can cause disastrous EMI and ringing if clock harmonics overlap resonant frequency
- Usually sets the package's ultimate useful bandwidth
- Hard to build a circuit model to account from them: requires coupling to many leads

Measured Resonances in 2 Leads

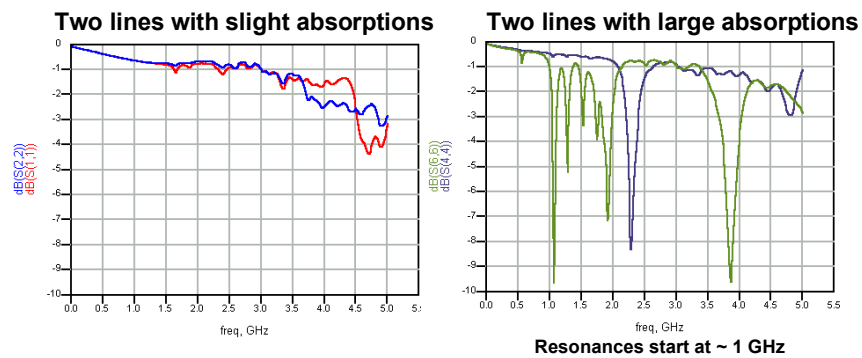
2 BGA leads, open far end, plotted as Log Mag vs. freq



Strong package resonances at 1.9 GHz, 4-5 GHz, 9.1 GHz
Some difference between the two leads

www.GigaTest.com

S_{11} for 4 Other Signal Leads Shorted to Gnd Plane at Wire Bond Shelf



Different leads coupled differently to each package resonance.
The only sure way of knowing where the resonances are is by *measuring*

This package may not be usable above 1 GHz!

www.GigaTest.com

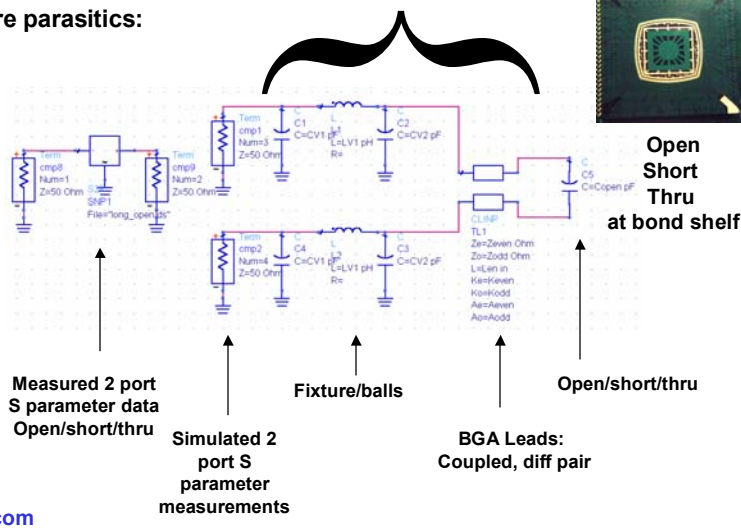
Case Study Examples

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Generic SPICE Compatible Model for 2 Adjacent Leads

Typical fixture parasitics:
 $C \sim 0.1 \text{ pF}$
 $L \sim 0.6 \text{ nH}$

Fixed for open/short/thru cases



Parameters to Optimize

Model Parameters:

- **Fixture:**
 - ✓ CV1
 - ✓ CV2
 - ✓ LV1
- **Termination:**
 - ✓ Lshort
 - ✓ Lshort_return
 - ✓ Copen
 - ✓ Lthru
- **BGA Leads**
 - ✓ Len = 0.448 in
 - ✓ Zeven = 70.5 Ohms
 - ✓ Zodd = 57.0 Ohms
 - ✓ Keven = 5.17
 - ✓ Kodd = 4.3
 - ✓ Aeven = 5 dB/m at 1 GHz

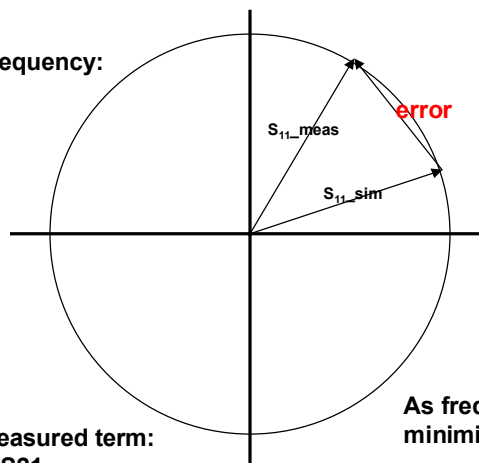
Extracted parameter values

Var	VAR
Eqn	VAR1
	CV1=.118 opt{ 0 to 1 }
	CV2=.121 opt{ 0 to 1 }
	LV1=0.642 opt{ 0 to 2 }
	Lshort=0.729 opt{ 0 to 2 }
	Lshort_return=0.673 opt{ 0 to 2 }
	Copen=0.14 opt{ 0 to 2 }
	Lthru=0.142 opt{ 0 to 1 }
	Len=0.448 opt{ .2 to .8 }
	Zeven=70.5 opt{ 40 to 90 }
	Zodd=57.0 opt{ 20 to 60 }
	Keven=5.17 opt{ 2 to 6 }
	Kodd=4.3 opt{ 2 to 6 }
	Aodd=5 opt{ 0 to 5 }
	Aeven=Aodd noopt{ 0 to 5 }

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The Optimization Goal

at each frequency:



For each measured term:

Open: S11, S21

Short: S11, S21

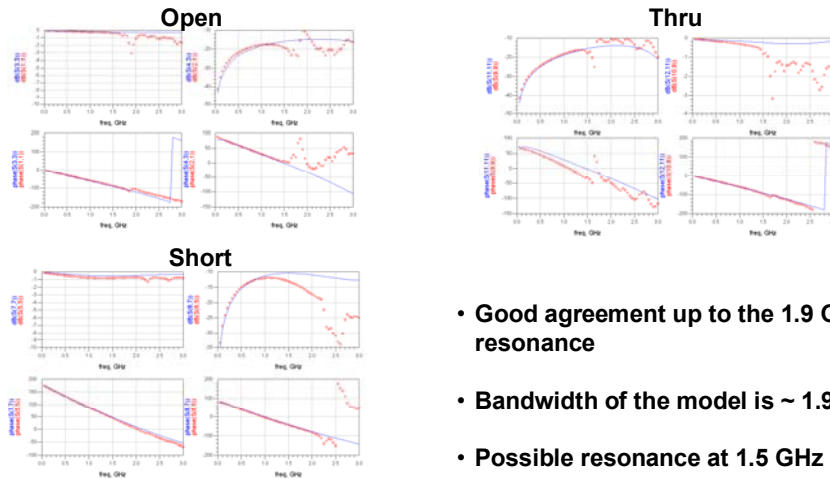
Thru: S11, S21

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As frequency is swept,
minimize:

$$\sum \text{error}^2$$

Measured and Optimized Model Simulation: up to 3 GHz

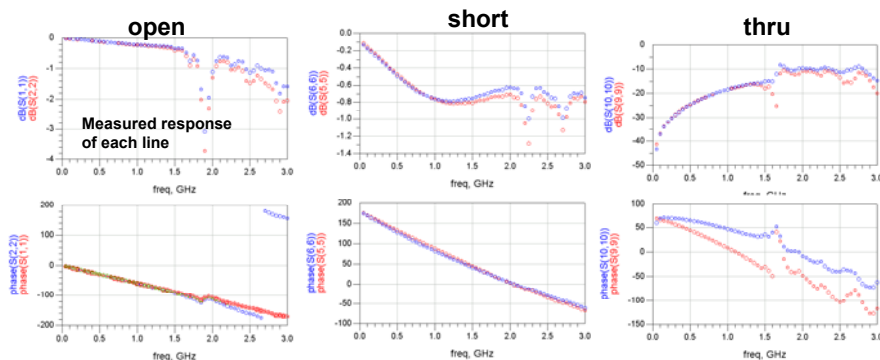


- Good agreement up to the 1.9 GHz resonance
- Bandwidth of the model is ~ 1.9 GHz
- Possible resonance at 1.5 GHz

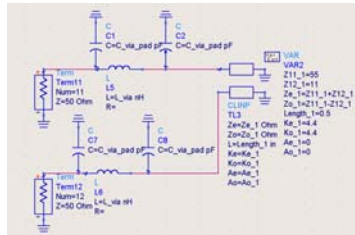
Simplifying Assumptions in the Model

- Assumptions
 - ✓ Both lines are symmetrical, uniform
 - ✓ Symmetrical fixturing
 - ✓ No coupling in fixture
 - ✓ Simple model for open/short/thru

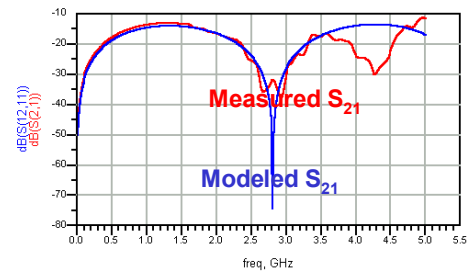
Conclusion:
There is some asymmetry



Higher Bandwidth BGA Package Example



S21, between the leads, far end shorted



De-embedded, extracted terms:

$Z_{\text{odd}} = 44 \text{ Ohms}$, $Z_{\text{even}} = 66 \text{ Ohms}$

$Z_{\text{diff}} = 2 \times 44 \text{ Ohms} = 88 \text{ Ohms}$

$Z_{\text{comm}} = \frac{1}{2} \times 66 \text{ Ohms} = 33 \text{ Ohms}$

Bandwidth of the model: 3.5 GHz

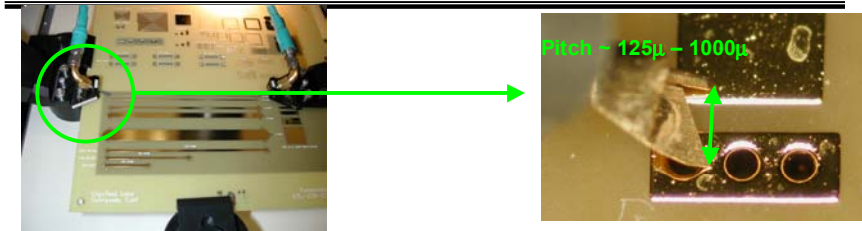
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Case Study Examples

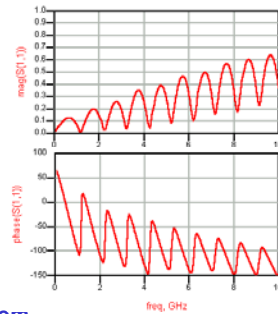
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 - ✓ Insertion loss, attenuation and bandwidth of the interconnect
- 4 Port complete differential pair characterization

www.GigaTest.com

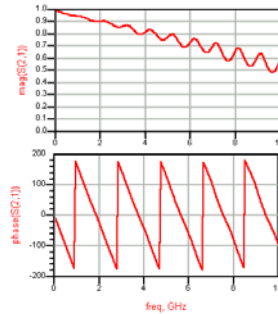
Insertion Loss and Return Loss for PCB Trace



Return Loss (S_{11})



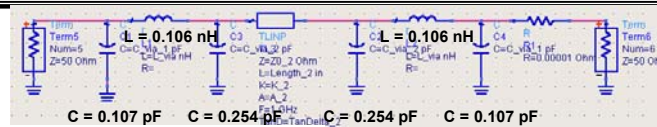
Insertion Loss (S_{21})



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Optimized for Parameters with Via Model

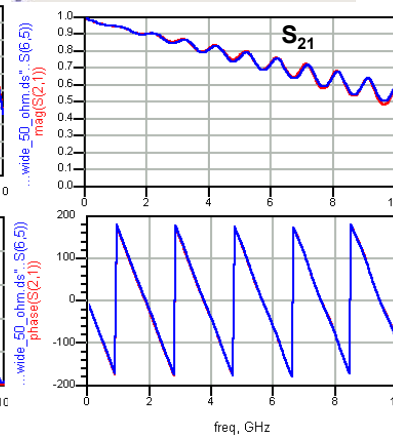
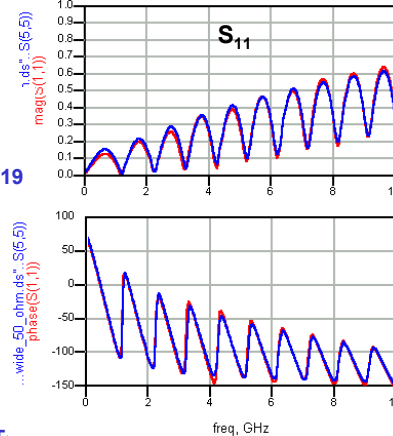
Topology:



Parameter values:

$Z_0 = 57.9 \text{ Ohm}$
 $A = 2.33 \text{ dB/m}$
 $\epsilon_{r_eff} = 4.0$
 $\tan(\delta) = 0.019$

All parameters constant up to 10 GHz!

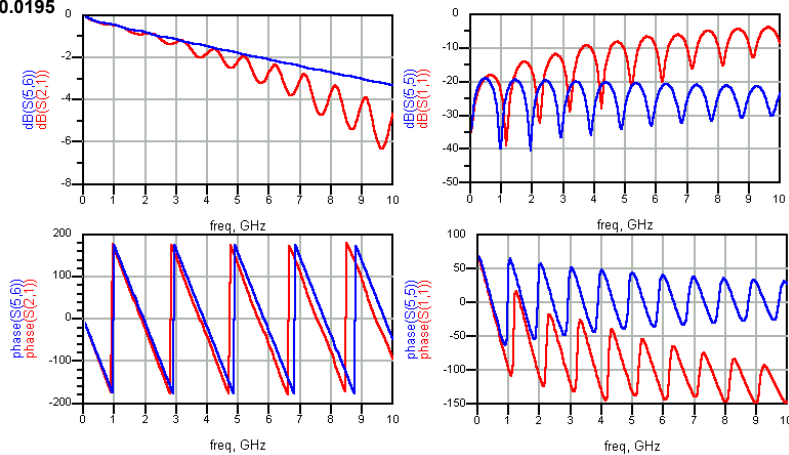


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How Important are the Vias?

$Z_0 = 56.15 \text{ Ohm}$
 $\epsilon_{r_eff} = 4.08$
 $A = 2.32 \text{ dB/m}$
 $\tan(\delta) = 0.0195$

Via terms set to 0



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Including Vias is **VERY** Important

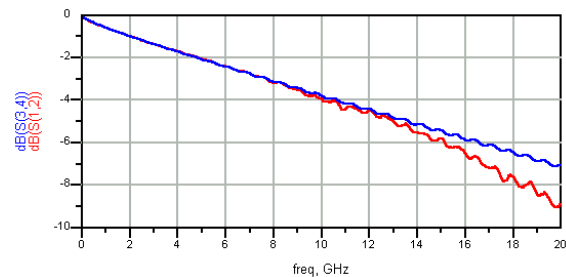
- DUT should be designed for minimum size vias
 - ✓ Probe parasitics also are critical for accurate measurements
 - ✓ Use microprobes to probe
 - ✓ Calibrate out the effects of the microprobes and cables
- Not including the vias will add artifacts to extracted dielectric properties:
 - ✓ Extracted dielectric constant will be higher than actual dielectric constant
 - ✓ Extracted dissipation factor will be higher than actual dissipation factor
 - ✓ May look like frequency dependence to the values
- Include a model for the vias with the lossy line model

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Measured and Simulated for 4 inch long 50 Ohm Stripline in FR4

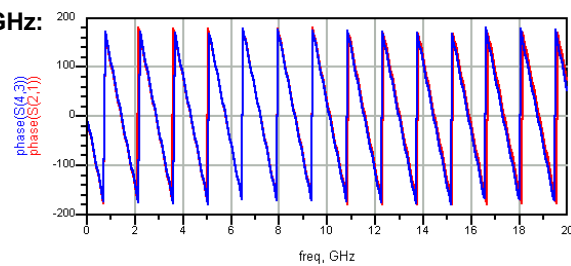
Parameter values:

$Z_0 = 51.3 \text{ Ohm}$
 $\epsilon_{\text{eff}} = 4.0$
 $A = 3.1 \text{ dB/m}$
 $\tan(\delta) = 0.0145$
 $TD_{\text{via}} = 8 \text{ psec}$
 $Z_{0_{\text{via}}} = 39 \text{ Ohms}$
 $L_{\text{via}} = 39 \times 8 \text{ psec} = 0.31 \text{ nH}$
 $C_{\text{via}} = 8 \text{ psec}/39 \text{ Ohms} = 0.2 \text{ pF}$



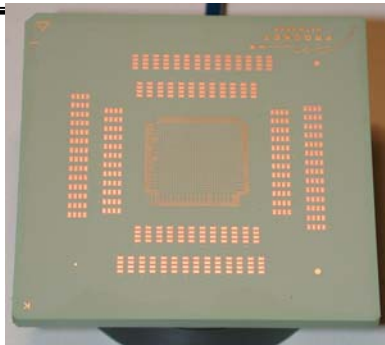
Constant from DC to ~ 10 GHz:

$\epsilon_{\text{eff}} = 4.0$
 $A = 3.1 \text{ dB/m}$
 $\tan(\delta) = 0.0145$



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Bandwidth of Package



LTCC
 10-20 conductor layer
 75 micron line width
 3k-6k flip chip bumps
 1k-2k land grid array pads

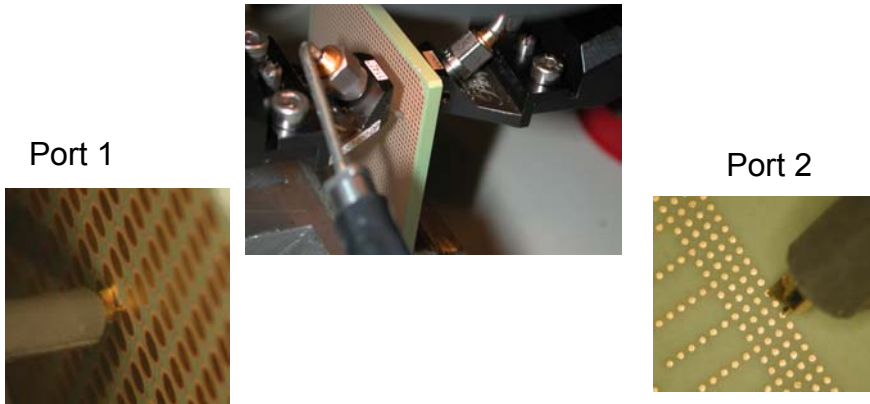
Desired Specifications:

1. Differential Impedance: 100 Ohms +/- 10% peak at 100 psec
2. -3 dB BW > 6 GHz
3. first major resonance at >10 GHz
4. Differential xtalk < 1% when terminated
5. Open eye pattern

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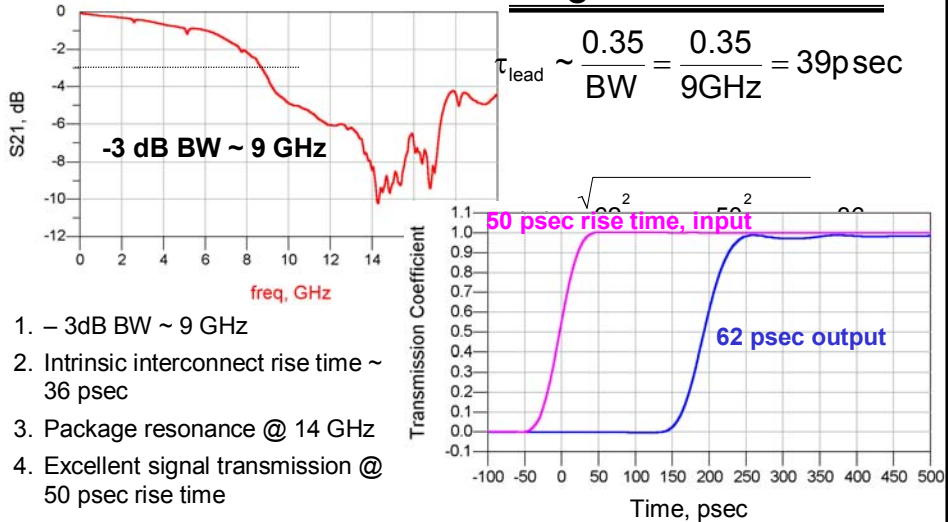
Single Trace Direct Through for 20 GHz Measurement

Direct through



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Measured Transmission with Direct Probing



1. - 3dB BW ~ 9 GHz
2. Intrinsic interconnect rise time ~ 36 psec
3. Package resonance @ 14 GHz
4. Excellent signal transmission @ 50 psec rise time

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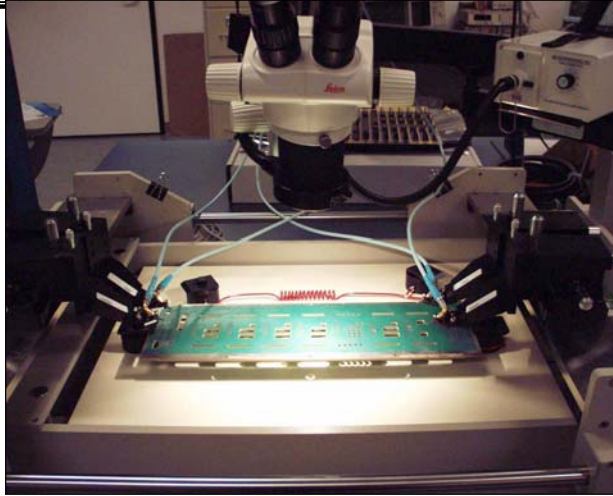
Case Study Examples

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4 Port VNA Measurements

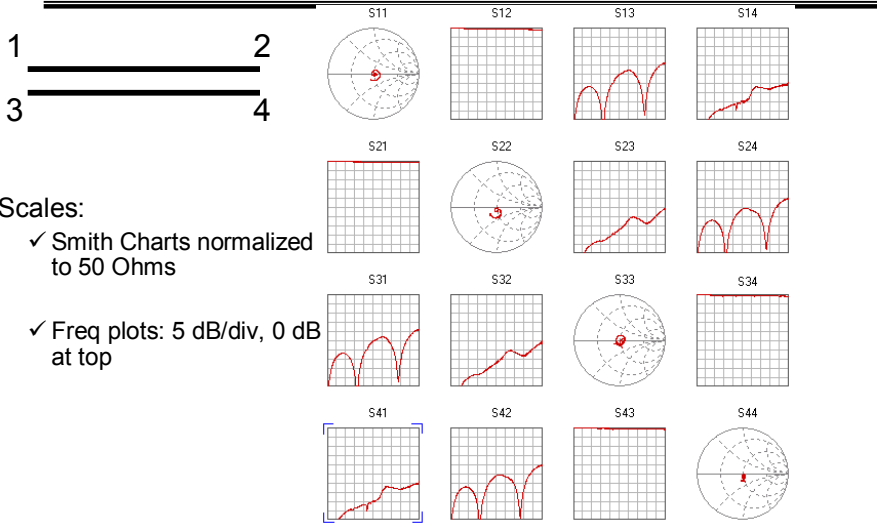


Fast, Complete Differential Pair Characterization with 4 port VNA Based System



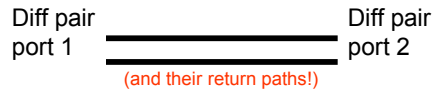
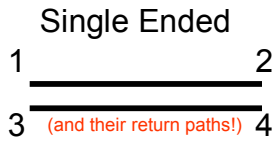
www.GigaTest.com

Measured 4 Port Single Ended S Parameters



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Converting Single Ended to Balanced S Parameters



Stimulus

Response	S_{11}	S_{12}	S_{13}	S_{14}
	S_{21}	S_{22}	S_{23}	S_{24}
	S_{31}	S_{32}	S_{33}	S_{34}
	S_{41}	S_{42}	S_{43}	S_{44}

Stimulus

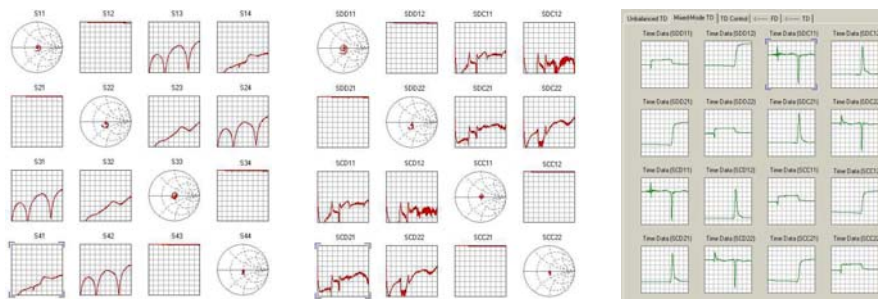
Response	Differential Signal		Common Signal	
	Port 1	Port 2	Port 1	Port 2
	Port 1	Port 2	Port 1	Port 2
Common Signal	S_{DD11}	S_{DD12}	S_{DC11}	S_{DC12}
Differential Signal	S_{DD21}	S_{DD22}	S_{DC21}	S_{DC22}
Port 2	S_{CD11}	S_{CD12}	S_{CC11}	S_{CC12}
Port 1	S_{CD21}	S_{CD22}	S_{CC21}	S_{CC22}

Data Management: 16 Element S Parameter Matrix

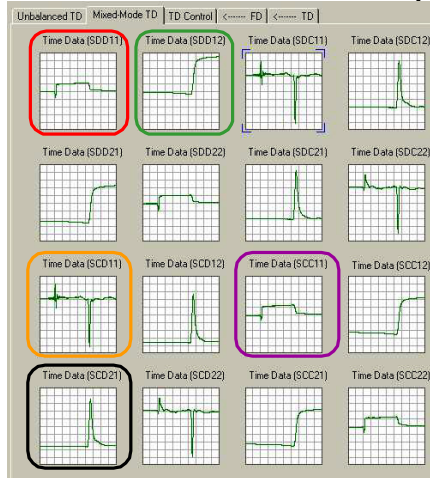
Single ended S Parameters

Mixed Mode S Parameters

Mixed Mode S Parameters Displayed in the Time Domain



Balanced Time Domain Response



Five important terms:

SDD11: Differential Impedance

SCC11: Common impedance

SDD21: transmitted diff signal

SCD21: mode conversion: diff signal in, common signal out

SCD11: mode conversion: diff signal in, common signal reflected back

Conclusions

- Even though it's the frequency domain, there is value for high speed digital applications
- It's more than just an instrument that makes the measurements: it's system solutions
- Critical ingredients
 - ✓ Probes
 - ✓ Instruments
 - ✓ Analysis software
 - ✓ Understanding

GigaTest Labs Courses in Signal Integrity Engineering

- GTL122 a SI 101: Fundamental principles of Signal Integrity
b SI 101: Fundamental principles of Transmission lines

- GTL250 a High speed board design: signals
b High speed board design: switching noise, ground bounce and EMI

- GTL260 a Creating high bandwidth models from measurement: 1st order models
b Creating high bandwidth models from measurement: high bandwidth

- GTL262 a Creating high bandwidth models from calculations : 1st order models
b Creating high bandwidth models from calculations : numerical simulation